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A METHOD AND APPARATUS FOR MEASURING THE PROPAGATION TIME OF A SIGNAL~~, IN PARTICULAR AN ULTRASOUND SIGNAL~~

The invention relates to a method and to apparatus for measuring the propagation time of signals, in particular ultrasound signals propagating between two transducers.

BACKGROUND OF THE INVENTION

A known method of measuring the time T_p taken by a signal, e.g. an ultrasound signal, to propagate between two transducers consists in exciting the emitter transducer with an excitation pulse IE1. Such an excitation pulse is substantially in the form of a squarewave and the frequency spectrum includes the excitation frequency of the transducer. On being emitted by the emitter transducer, this pulse gives rise to an ultrasound wave in the medium between the two transducers. This wave will propagate towards the receiver transducer. Figure 1 shows the excitation signal IE1 of the emitter transducer and the signal SR1 as output by the receiver transducer. The method consists in detecting the first oscillation of said wave on arrival at the receiver transducer. The propagation time T_p is then the time between the instant at which the emitter transducer is subjected to the excitation pulse and the instant at which the first oscillation of the ultrasound wave is detected as arriving at the receiver transducer. That method is particularly difficult to implement and suffers from inaccuracy that gives rise to an erroneous measurement of propagation time. At the receiver transducer, the ultrasound wave gives rise to a response signal of very low amplitude. By way of example, in the context of an ultrasound flow meter used in heating networks, for a transducer having a resonant frequency close to 10 megahertz (MHz), the amplitude response of a received signal corresponds to a value lying in the range about 3 millivolts (mV) to 10 mV. Figure 2 shows the appearance of the response signal from

the receiver transducer SR1 when the emitter transducer is excited by a single pulse. The method consists in detecting the first oscillation of the ultrasound wave PF1 by detecting when a voltage threshold is crossed. That method requires very low voltage levels to be detected and very accurate control over the trigger threshold of the device for detecting the arrival of an oscillation in order to avoid introducing any delay in the propagation time measurement. That method can be made to be accurate by using an electronic threshold trigger component that is of high performance, but expensive. However, it becomes inaccurate when using an electronic threshold trigger component of ordinary type.

US patent 5 123 286 discloses a method of determining the propagation time of an ultrasound wave between two transducers. The emitter transducer is excited by a squarewave pulse which gives rise to the appearance of a response signal that is typical for a damped oscillator whose peak amplitude increases over a certain number of periods before decreasing. That method proposes determining the propagation time between the instant at which the emitter transducer is excited and the instant at which the ultrasound signal is received by the receiver transducer. It consists in calculating an envelope for the response signal by determining firstly the amplitude of a group of periods and secondly the instants of the zero crossings of said periods. The point where said envelope intersects the baseline of the response signal is then calculated in order to determine the instant at which the response signal appears at the transducer. Finally, the propagation time is determined by calculating the difference between the excitation instant and said instant at which the signal appears. That method is complex to implement, and requires a plurality of measurements to be made and stored, and numerous calculations to be performed.

OBJECTS AND SUMMARY OF THE INVENTION

The present invention thus provides a method of measuring the propagation time T_p of an ultrasound signal between two spaced-apart transducers, one constituted by an emitter and the other by a receiver, the emitter transducer being subjected to an excitation signal causing an ultrasound wave to be emitted towards the receiver transducer, said ultrasound wave causing the receiver transducer to output a receive signal, the method being characterized in that it comprises the following steps:

· beginning a measurement of an intermediate propagation time T_{int} at the beginning of emitter transducer excitation;

· detecting the receive signal output by the receiver transducer and counting the oscillations in said receive signal;

· stopping the measurement of the intermediate propagation time T_{int} when an i^{th} oscillation is detected; and

· determining the propagation time T_p of the signal by taking the difference $T_{int} - i \times T_e$.

Advantageously, the excitation signal is constituted by <u>n</u> pulses, where $n \neq 1$, and the measurement of the intermediate propagation time T_{int} is stopped on an i^{th} oscillation of the receive signal, where $i \neq 1$.

In a first implementation, measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal that corresponds to the receive signal being at a maximum amplitude.

In a second implementation, the measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal, where $i=n$.

In a first particular implementation, the number of pulses <u>n</u> making up the excitation signal is preferably $n=4$ or $n=5$, and measurement of the intermediate

propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal, preferably where i=4 or i=5.

The response of the transducer to the train of n pulses corresponds to the transient response of an oscillator to periodic excitation. The peak amplitude of such a receive signal increases very quickly during the initial periods of the signal and then stabilizes on a constant amplitude. A first advantage is that the amplitude of the i^{th} oscillation is greater when responding to a train of n pulses (where n>1) than when responding to a single excitation pulse. Another advantage of measuring propagation time on an i^{th} oscillation selected in appropriate manner is that it becomes possible to measure propagation time using a signal of amplitude that is much greater than that of the first oscillation of the receive signal. Thus, firstly the trigger threshold can be small relative to the peak amplitude of the receive signal, which means that the delay introduced by the time taken by the receive signal to reach the trigger threshold is much smaller for the i^{th} oscillation than for the first oscillation, and secondly this method makes it possible to use a standard trigger threshold comparator without any need to monitor its trigger threshold accurately, while still considerably improving the accuracy with which propagation time is measured.

The present invention also provides apparatus for measuring the propagation time T_p of an ultrasound signal, the apparatus comprising:

· means for forming an excitation signal;

· an emitter transducer 1, 2 connected to said means for forming an excitation signal;

· a receiver transducer to transform the ultrasound signal into a receive signal; and

· comparator means connected to said receiver transducer to compare the amplitude of the receive signal

with a trigger threshold voltage and to generate a signal representative of oscillations of said receive signal;

said apparatus further comprising:

· means for measuring a fixed time T_0 connected to said means for forming an excitation signal in order to measure a fixed time T_0 from the instant at which the emitter transducer is excited;

· means for determining an i^{th} oscillation, which means are connected to said comparator means, to count the number of oscillations in the receive signal and to detect the i^{th} oscillation; and

· means for measuring a variable time T_{IEX} between the end of measuring T_0 and detecting the i^{th} oscillation.

BRIEF DESCRIPTION OF THE DRAWINGS

Other characteristics and advantages appear from the following description given by way of non-limiting example and made with reference to the accompanying drawings, in which:

· Figure 1 shows the excitation signal of the emitter transducer and the signal output by the receiver transducer as a function of time for a prior art measurement method;

· Figure 2 shows the appearance of the receiver transducer response signal as a function of time when the emitter transducer is excited by a single pulse in a prior art measurement method;

· Figure 3 shows the excitation signal of the emitter transducer and the signal output by the receiver transducer as a function of time in the measurement method of the invention;

· Figure 4 shows the appearance of the receiver transducer receive signal as a function of time when the emitter transducer is excited by a train of pulses in a measurement method of the invention;

· Figure 5 shows the amplitude of the receiver transducer receive signal for the first oscillation and for the i^{th} oscillation;

· Figures 6a to 6d are diagrams of various electronic circuits enabling the method of the invention to be implemented; and

· Figure 6 shows timing diagrams for various signals associated with the electronic circuits of Figures 6a to 6d.

MORE DETAILED DESCRIPTION

Figure 3 shows the excitation signal IEn for exciting the emitter transducer and also the receive signal SRn as measured at the output from the receiver transducer. The propagation time T_p that is to be measured is the time that elapses between the instant when the excitation signal is sent to the transducer and the instant when the resulting ultrasound signal reaches the receiver transducer.

The excitation signal IEn comprises a succession of n pulses, e.g. having a duty ratio of 0.5. The number of pulses n making up the excitation signal is such that $n \neq 1$. The frequency spectrum of each pulse includes at least an excitation frequency T_e close to the resonant frequency of the transducer, e.g. 1 MHz. Thus, since the transducer is comparable to an oscillator, when it is subjected to a succession of pulses, each pulse being substantially in the form of a squarewave, it will be put into conditions of sustained periodic oscillation, for a length of time that is associated with the number of pulses making up the excitation signal. The ultrasound signal emitted by the emitter transducer towards the receiver transducer through the medium between the two transducers results from the excitation signal whose characteristics are described above. At the receiver transducer, this wave gives rise to the receive signal SRn. The ultrasound signal and the resulting electrical receive signal as output by the receiver transducer typically have the form of a packet of waves, i.e. of an oscillation of amplitude that increases, reaches a maximum, and subsequently decreases. Since amplitude

decreases when the emitter transducer is no longer subjected to the excitation signal, the signal then behaves as a damped oscillation.

Figure 4 shows a portion of the receive signal measured at the output from the receiver transducer. Figure 5 shows the amplitude of this signal for its first oscillation and for its i^{th} oscillation.

The first oscillation P1 of the receive signal has an amplitude $V_{max}(1)$ that is low, but nevertheless greater than the trigger threshold V_{trig}, enabling it to be detected by a suitable electronic circuit. However, the i^{th} oscillation Pi of the receive signal has an amplitude $V_{max}(i)$ which is much greater than the trigger threshold V_{trig}. It is therefore clear that the error in measuring time that corresponds to the precise instant at which the threshold voltage crossing is detected decreases with increasing amplitude. Consequently, the error on the i^{th} osculation Pi is much smaller than the error on the first oscillation P1. In order to minimize error in measuring propagation time, it is therefore preferable to measure an intermediate propagation time on the i^{th} oscillation, and then correct the measurement by subtracting the time that elapses between the first oscillation and the i^{th} oscillation being detected.

Advantageously, measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal, where $i \neq 1$. In a particularly advantageous implementation, measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal that corresponds to the receive signal being at a maximum amplitude.

In another implementation, measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal, where $i=n$.

Figures 6a to 6d are described below in association with Figure 7. Figure 7 gives timing diagrams for the signals involved in the electronic circuits of Figures 6a

to 6d. In all of Figures 6a to 6d, a battery (not shown) supplies the power required for causing the various electronic components to operate via suitable cabling known to the person skilled in the art.

Such apparatus finds an application in particular in the field of ultrasound flow metering. The two transducers 1, 2 are disposed in a fluid flow, with the transducer 1 acting alternately as an emitter and then as a receiver, with the transducer 2 being in the opposite state to the transducer 1. The time taken by ultrasound waves to propagate through the flowing fluid between the two transducers 1, 2 in the upstream direction T1 and in the downstream direction T2 makes it possible to calculate the fluid flow rate Q as a function of a defined term K associated with the geometry of the flow meter:

$$Q \approx \frac{4 \times K \times |T2 - T1|}{(T1 + T2)^2}$$

Figure 6a is a diagrammatic view of the circuit which controls emission and reception of ultrasound waves by the transducers 1, 2. During emission stages, a microcontroller (not shown) causes an emission signal ST1, ST2 (see Figure 7) to be applied to the corresponding transducer 1, 2. The emission signal ST1, ST2 comprises a train of $\underline{n}$ pulses at a frequency fe, e.g. 1 MHz. The pulse train is synchronous with a clock signal CLK1.

In Figure 6a, the transducers 1, 2 are of the type comprising a piece of piezoelectric material having two metallized surfaces, one of which is connected to ground (0) and the other to a respective switch U3, U4. When the transducer 1 is subjected to an excitation signal ST1 and emits an ultrasound signal towards the transducer 2, the switch U3 is open while the switch U4 connected to the transducer 2 in receive mode is closed. The configuration of the switches is inverted when the

transducer 2 is subjected to the excitation signal ST2 and the transducer 1 is in receive mode. The switches U3, U4 are controlled by the microcontroller (not shown) in conventional manner. The output voltage VS1, VS2 from the respective transducer 1, 2 is applied to the inverting input of a comparator U5. The comparator U5 is powered by the voltage Vdd via a V+ input. A V- input of the comparator U5 is connected to ground 0. Its non-inverting input is connected to a reference voltage referred to as the trigger voltage Vtrig. The output from the comparator is connected to an inverter U6. Thus, the receive signal SIG is available at the output from the comparator unit U5, U6, which is adjusted for a detection threshold Vtrig. When the voltage threshold Vtrig is exceeded, a low or "0" state appears at the output from the comparator U5, and when the signal lies below the voltage threshold it delivers a high or "1" state. The signal SIG (see Figure 7) supplied by the circuit of Figure 6a is thus representative of the receive signal supplied by the emitter transducer, each pulse in the signal SIG corresponding to a positive half cycle of an oscillation in the receive signal.

Figures 6b, 6c, and 6d are diagrams of circuits for measuring propagation time. Propagation time is determined by adding two time contributions. Firstly, a first circuit shown in Figures 6b and 6d serves to count a fixed length of time T_0, and then a second circuit as shown in Figure 6c serves to measure the time that remains between T_0 and the instant corresponding to the corresponding signal being detected on its i^{th} oscillation. To determine this remaining time, which time is variable, it must be possible to measure a short duration, which cannot be done by using conventional means such as a clock and a high frequency counter, for example. This problem can be overcome by using a time expander circuit. The principle on which a time expander circuit operates is already described in patent

FR 2 750 495. The time expander circuit HB5 multiplies the duration of a pulse by a time multiplication factor specific to the time expander circuit. The expanded time interval output from the circuit HB5 can be measured in conventional manner, thus making it possible to deduce the duration of the pulse by dividing the duration of the expanded time interval by the multiplication factor.

In Figure 6b, a logic OR gate U7 has one of its two inputs receiving the signal ST1 and its other input receiving the signal ST2, and it has its output connected to the input LAT of a D-type bistable U8. Thus, when a signal ST1 or ST2 is present on one of the inputs of the gate U7, that signal is applied to the input LAT. The two inputs S and D of the bistable U8 are at the potential Vdd, i.e. in a high state, while the input $\overline{R}$ is subjected to an initialization signal RG. The output $\overline{Q}$ of the bistable U8 is floating. The other output Q from the bistable U8 is connected to an AND gate U9 whose other input is subjected to the clock signal CLK1. Thus, after the bistable U8 has been initialized, as soon as a signal ST1 or ST2 is present on the input LAT, the output Q of the bistable switches to the high state. The signal output by the logic gate U9 then becomes the clock signal CLK1. The output from the logic gate U9 is connected to the CLK input of counter HB1 which possesses an input R subjected to the initialization signal RG. The counter HB1 thus counts the number of periods reaching its CLK input after initialization by RG. The output from the counter HB1 is connected to the input of a decoder HB2, which in turn outputs a signal OSP representative of the fixed time interval T_0. This duration T_0 corresponds to the duration during which the signal OSP is in a low state.

This circuit therefore acts to measure a fixed length of time T_0 starting from the first change in state caused by a signal ST1 or ST2 reaching one or other of the inputs of the gate U7.

Once the first duration T_0 has been measured, the second circuit shown in Figure 6c determines the remaining duration between the end of the count corresponding to T_0 and the i^{th} oscillation in the receive signal SIG being detected.

Initially, it is necessary to detect the i^{th} oscillation. This task is performed by the circuit shown in Figure 6d. This circuit has a counter HB3 having an R input and a CLK input, which inputs are subjected to the initialization signal RG and to the receive signal SIG, respectively. After initialization, on arrival of the signal SIG, the counter counts the number of pulses in the receive signal SIG. The inputs of the decoder HB4 is connected to the output of the counter HB3 such that when the counter reaches the i^{th} pulse, the detection signal ESP output from the decoder HB4 passes from the low state to the high state during one period of the receive signal SIG (see Figure 7).

The circuit of Figure 6c serves to determine the very short duration that elapses between the end of T_0 count and detection of the i^{th} oscillation, and it does this by means of the time expander circuit HB5. A first D-type bistable U12 has its D and S inputs connected to the potential Vdd and has its $\overline{R}$ input subjected to the initialization signal RG, while its input LAT receives the signal OSP which marks the end of the time during which T_0 is being measured by switching to the high state (see Figure 6b and Figure 7). The output $\overline{Q}$ from the bistable U12 is floating. The output Q passes to a high state when the signal OSP passes from the low state to the high state. The output Q of the bistable U12 is connected to the input D of the bistable U13 and to the input LAT of the bistable U14. The inputs S, LAT, and $\overline{R}$ of the bistable U13 are subjected to the potential Vdd, to the detection signal ESP, and to the initialization signal RG, respectively. The output Q of the bistable U13 is floating while the output $\overline{Q}$ is connected to the

input $\overline{R}$ of the bistable U14. Thus, once the signal OSP passes from a low state to a high state after T_0 has been measured, and the detection signal ESP passes to a high state on detecting the i^{th} oscillation, the output $\overline{Q}$ passes from a high state to a low state, forcing the output Q of the bistable U14 to zero (signal IEX). The inputs S and D of the bistable U14 are at the potential Vdd. The output $\overline{Q}$ of the bistable U14 is floating. The output Q of the bistable U14 supplies the signal IEX which is in the high state when the signal OSP passes to the high state and for so long as the detection signal ESP has not switched from the low state to the high state. The signal IEX is thus a pulse whose high state begins at the end of measuring the duration T_0 and ends when the i^{th} oscillation is detected. The time expander HB5 processes the signal IEX so that the duration T_{IEX} during which the pulse corresponding to the signal IEX is in the high state is multiplied by a factor T_{fm}. The resulting signal at the output from the expander HB5 is the signal IEX_EXP.

The two signals OSP and IEX_EXP are processed by a microcontroller (not shown) which determines the intermediate propagation time, e.g. for an ultrasound wave propagating between the transducers 1 and 2:

$$T_{int} = T_0 + \frac{T_{IEX}}{T_{fm}}$$

Thereafter, the microcontroller determines the propagation time T_p as a function of the selected number $\underline{i}$ and of the period of the excitation signal ST1 of the transducer:

$$T_p = T_{int} - i \times T_e$$

All of the above-described electronic circuits can be integrated in an application specific integrated circuit (ASIC). The number $\underline{n}$ of pulses making up the excitation signal and the number $\underline{i}$ determining which oscillation of the receive signal is used for measuring

propagation time can be programmed in the ASIC or in the software managing the ASIC and the data it provides.

Advantageously, measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal that corresponds to the receive signal being at a maximum amplitude.

By way of example, and in the field of an ultrasound flow meter using meters having ultrasound transducers with a resonant frequency close to 1 MHz, the ASIC and the software are programmed in such a manner that the number of pulses n making up the excitation signal is preferably n=4 or n=5, and measurement of the intermediate propagation time T_{int} is stopped for an i^{th} oscillation of the receive signal such that, preferably i=4 or i=5. Furthermore, the method and the apparatus of the invention when applied to ultrasound flow measurement make it possible to improve the accuracy of measurement significantly, enabling an error of less than 0.5% to be achieved on propagation time measurement, while nevertheless using an ordinary threshold trigger component of low cost and that consumes little energy.

Although the invention is described above with reference to ultrasound waves, it is clear that it is not limited to this type of wave, and the person skilled in the art can transpose the method to any other type of wave, for example electrical or electromagnetic waves. The same applies to the apparatus for measuring propagation time.